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AMPLIFICATION MECHANISMS IN LIQUIDITY CRISES

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ABSTRACT

I describe two amplifications mechanisms that operate during liquidity crises and discuss the scope for central bank policies during crises as well as preventive policies in advance of crises. The first mechanism works through asset prices and balance sheets. A negative shock to the balance sheets of asset-holders causes them to liquidate assets, lowering prices, further deteriorating balance sheets, culminating in a crisis. The second mechanism involves investors' Knightian uncertainty. Unusual shocks to untested financial innovations lead agents to become uncertain about their investments causing them to disengage from markets and increase their demand for liquidity. This behavior leads to a loss of liquidity and a crisis.

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1 Introduction

We have seen (are seeing) a financial crisis in which relatively small losses on subprime assets have triggered a process leading to large reductions in wealth and output. The direct losses due to household default on subprime mortgages are estimated to be at most \$500 bn, yet the effects of the subprime shock have been far reaching (see, e.g., Brunnermeier, 2008, Gorton, 2008, or Blanchard, 2009, on the current crisis). Observers are blaming leverage, maturity mismatch, tight credit conditions, limited capital, opacity, complexity, uncertainty, and suggesting various policy actions.

This paper offers a simple framework to clarify the *financial amplification mechanisms* that are at work during the crisis and explore the potential role of policy. By financial amplification mechanisms, I mean the mechanisms involving the financial sector that can lead a small shock to have a large effect. Broadly speaking, the factors that many observers point to can be classified into balance sheet amplifiers (e.g., leverage, tight credit conditions, limited capital) and information amplifiers (e.g., opacity, complexity, uncertainty). I present a simple model to discuss these two mechanisms.

The paper can be thought of as a literature survey around a model. The balance sheet amplification mechanism is the subject of an extensive literature and is often the first reference during financial crises. For example, in the 1998 hedge fund crisis, the Russian default triggered a chain of losses that culminated in the bailout of Long Term Capital Management. There was contagion, as the Russian default led to effects in seemingly unrelated markets such as the mortgage-backed securities market.[1] The 1998 event has served as motivation for a literature that describe the following mechanism: a negative asset price shock causes balance sheet constraints on asset-holders to tighten, causing assets to be liquidated, lowering asset prices further, and so on. There are different versions of this mechanism, involving leverage, margin requirements, limited capital, and shedding light on asset fire sales, asset market volatility, contagion, etc. I discuss some of the variants of the balance sheet mechanism that appear in the literature.

I next review an information amplification mechanism that works through agents' uncertainty. Many liquidity crises surround financial innovations that were rapidly adopted by market participants. In the subprime crisis, the CDOs and associated credit derivatives that are at the center of the crisis, represent financial assets that have grown from less than \$1 tn in 2000 to over \$5 tn today. New innovations necessarily mean that market participants have a short time within which they formulate valuation, risk management, and hedging models. A liquidity crisis occurs when the new financial assets behave in unexpected ways.

[1] For further details on the 1998 crisis, see Scholes (2000).

Lacking a historical record to refer to, market participants are faced with risks they don't understand, and treat these risks as Knightian (Knight, 1925). Investors' response in this case is to disengage from risks and seek liquid investments, which can lead to a liquidity crisis dynamic. The main paper that I draw from in discussing this mechanism is Caballero and Krishnamurthy (2008).

Thus, one objective of this paper is to clarify these two amplification mechanisms and discuss their relevance during the present, and past, crises. The second objective of the paper is to clarify the role for policy during a financial crisis. In both models, there is a scope for ex-post policies, such as liquidity provision through a lender of last resort. The same forces that underly the negative-shock amplification mechanism also lead to a beneficial amplification of central bank liquidity provision. There is also scope for ex-ante policies, particularly in the balance sheet amplification mechanism. The private sector generally will not internalize the full costs of a crisis. This opens the door to investigating preventive policies in the form of liquidity requirements and capital requirements on the financial sector. I discuss the scope for these policies in both amplification mechanisms.

This paper is organized as follows. The two amplification mechanisms mentioned above are described in Sections 2 and 3. In Section 4, I discuss the senses in which the model outcomes reflect the "lack of liquidity" that many observers refer to in a crisis. In doing so, I also discuss how liquidity is measured in the empirical literature. Section 5 concludes.

2 Amplification through Balance Sheets and Asset Prices

Most investors in the sophisticated financial markets affected by liquidity crises – i.e. the mortgage and credit markets in the current subprime crisis, or the sovereign debt and derivative markets of the 1998 crisis – are financial intermediaries who are managing the funds of an ultimate household. Examples of these investors are hedge funds or banks, as well as pension funds and mutual funds. Theory then suggests that there may be agency conflicts between the household-investor and the intermediary that can affect the intermediary's investment decisions. As in corporate finance, where a similar manager-shareholder conflict arises, the intermediary's investment will depend on external financing conditions and the condition of its balance sheet.[2]

[2]Shleifer and Vishny (1997) identify this agency conflict and describe it as a "limit to arbitrage." That is, in textbook finance, it is common to argue that if asset prices deviate from fundamentals, an arbitrageur will step in to profit from the deviation. As a result, the argument goes, prices will remain close to fundamentals. Shleifer and Vishny make the important point that

Hedge funds raise equity from a clientele that is a combination of the managers of the hedge fund and wealthy households/institutional investors. They raise debt, mostly in the form of repo financing, from other investors.[3] Thus a hedge fund manages the funds contributed via both debt and equity contracts of some ultimate household. If hedge funds have lost money, or if they are holding particularly illiquid assets during a period of market illiquidity, investors may be unwilling to invest in either the equity or debt of the hedge fund. In this case, the hedge fund may have to reoptimize its portfolio, selling some assets and holding more liquid assets.

Mutual funds raise moneys predominantly through equity contributions of households. A well documented regularity is that the investors in mutual funds withdraw their funds following poor performance. Again, there is a relationship between the investment decisions of the mutual fund and its balance sheet (or change thereof).

If asset prices depend on the health of investors' balance sheets, then a feedback mechanism emerges whereby a negative shock in the financial market worsens balance sheets, reducing asset prices, feeding back into balance sheets, and so on. I model this feedback and dependence on balance sheets.

2.1 Balance Sheet Constraint

The model has a unit measure of investors. I will label these investors as hedge funds. But one can equally think of them as banks or institutional investors. I study a model in which the investment decisions of these hedge funds are a function of the health of their balance sheets.

The hedge funds purchase an asset at date s at price P_s. They may need, for exogenous and endogenous reasons, to liquidate the asset at a later date t at price P_t. In this section, I focus on the equilibrium price determination at date t.

At date s, the hedge fund raises debt from households of d_s and equity of $P_s - d_s$, so that the total funds raised are exactly enough to buy one unit of the asset. At date t, there are two states that may realize. In state $\omega = B$, one-half of the hedge funds (randomly chosen) have to liquidate their asset holdings and exit the market. The liquidation need is exogenous to the model. However, as outlined below, the exogenous

the textbook arbitrageur is someone like a hedge-fund manager who is investing the moneys of a household. Agency conflicts will place limits on to what extent the arbitrageur can exploit profit opportunities. The Shleifer and Vishny observation has spawned a large empirical and theoretical literature on the limits to arbitrage.

[3] A repo, or repurchase agreement, is a short-term debt contract that is collateralized by a financial asset. For many hedge funds, the predominant financing tool is a one day repo agreement, that is renewed every day.

liquidation may trigger endogenous liquidation by even those with no exogenous shock. In state $\omega = G$, there are no exogenous liquidation shocks. In the subprime context, we may imagine that the liquidity shock is a loss in the hedge fund's subprime investments that necessitates rebalancing its portfolio and forcing a sale of the asset at price P_t.[4]

Define the equity capital of the hedge fund at date t as,

$$w_t = P_t - d_s.$$

This equity capital can also be thought of as the balance sheet liquidity of the hedge fund. That is, since the hedge fund could sell the asset at date t at price P_t and repay d_s of debt, the difference $P_t - d_s$ reflects the liquid resources available to the fund.

For now, I fix the debt level of d_s exogenously and moreover assume for simplicity that the debt carries no interest. I also assume that the debt level is lower than the lowest possible price at date t, so that the debt can always be fully repaid. That is denote $\underline{P}$ as the lowest value attained by P_t. Then, $d_s < \underline{P}$.[5]

Suppose that the date t holdings of the fund are subject to a margin constraint. Define θ_t as holdings of

[4] The only shock in the model is the exogenous liquidation need. The crisis literature often uses this modeling device and examines how particular features of the economy may lead such a shock to cause a crisis. Diamond and Dybvig (1983), for example, study how the exogenous liquidity needs of households who are the depositors in a bank can lead to a banking crisis. There is a deeper question of where these household liquidity needs come from. Eisfeldt (2007) writes a model of a household whose income process may be different than its desired consumption process. The discrepancy gives rise to a demand for liquid assets. However, Eisfeldt shows that a realistic calibration of the model does very poorly in generating the magnitude of liquidity premia on assets that are observed in practice. Faced with a liquid, low return asset, and an illiquid, high return asset, households time their purchases of illiquid assets to take full advantage of the high return asset without incurring any of its illiquidity costs. In short, in equilibrium, households' liquidity needs vanish and there is no demand for the low-return liquid asset. The result is echoed in other papers in the literature (e.g., Heaton and Lucas, 1996) and suggests that we need a theory of liquidity demand that does not center on households' consumption needs. Here are some approaches that seem promising. Vayanos (2004) presents a model of delegated fund management in which households withdraw funds from a mutual fund following poor performance. As a result, the mutual fund manager alters his portfolio to favor liquid over illiquid assets, as household withdrawal states appear more likely. In this approach, there are no "true" liquidity needs in the economy. However, the inflexibilities that arise in contractual relationships between households and intermediaries create an endogenous source of liquidity demand. Holmstrom and Tirole (1998) and Eisfeldt and Rampini (2007) study corporate liquidity demand. In their models, firms face external financing constraints that prevent them from undertaking all good investment opportunities. This possibility leads them to insure, ex-ante, against those states in which the constraints are most tightly binding. The insurance can be represented as a demand for liquid assets, which the firm can then use in the needed state.

[5] The debt contract of the model resembles fully secured repo financing.

the fund at date t (after any liquidations). The constraint is that,

$$m\theta_t \leq w_t. \tag{1}$$

The fund must have equity capital commensurate to the size of its asset market position. We may think of m as a margin requirement per unit of asset holding, so that to hold θ_t units of the asset, the fund must put up total margin of $m\theta_t$.

Note that since w_t is decreasing in P_t, the balance sheet constraint tightens as market prices falls. In this sense, the constraint reflects an important feature of crises: market conditions and financing conditions worsen at the same time. The interpretation of m as a margin is close to Brunnermeier and Pedersen (2008) who develop the margin interpretation of this constraint in depth, discussing the institutional rationales for a such a margin constraint.

If we step back from the margins interpretation of constraint (1), it is worth noting that there are other balance sheet constraints that appear in the literature which are close to (1) and importantly preserve the relation between the constraint and market prices.

Kiyotaki and Moore (1997) develop a model in which lenders limit the debtor's investments based on pledged collateral. Suppose that the assets of θ_t can be pledged as collateral to a lender who forwards up to $\gamma\theta_t P_t$ against these assets (where $\gamma < 1$). Then, to purchase θ_t units of asset, the budget constraint for the hedge fund is,

$$\theta_t P_t \leq \gamma\theta_t P_t + w_t$$

or, rewriting,

$$(1-\gamma)P_t\theta_t \leq w_t. \tag{2}$$

This constraint, if we define $m = (1-\gamma)P_t$, is identical to the constraint (1). There is a price dependence on m which makes it different. However, in spirit, this constraint also preserves the effect that a reduction in w_t causes θ_t to fall.[6]

He and Krishnamurthy (2008a) develop a model in which an incentive conflict affects the participation of outside investors in a fund. In their model, a hedge fund manager as part of an optimal contract is required to put up some of his own wealth into the fund. Denote the manager's wealth as w_t. He and Krishnamurthy

[6] To see this, substitute $w_t = P_t - d_s$ into equation (2), to find that,

$$(1-\gamma)\theta_t \leq 1 - \frac{d_s}{P_t}.$$

As P_t falls, the right hand side of this equation falls, tightening the constraint and thereby reducing θ_t.

derive a contract whereby outside investors are willing to coinvest in the fund, at most, a multiple $\mathcal{M}$ times the manager's investment in the fund. The coinvestment constraint implies that the total funds that are under management by the hedge fund must be less than $w_t + \mathcal{M} w_t$. With these funds, the manager purchases θ_t units of assets. Then the fund's budget constraint is,

$$P_t \theta_t \leq w_t (1 + \mathcal{M})$$

or,

$$\frac{1}{1 + \mathcal{M}} P_t \theta_t \leq w_t \tag{3}$$

This constraint is identical to (2), and again preserves the key interaction between w_t and the asset position θ_t. The fact that there are many contexts in which a constraint similar to (1) arises indicates that the balance sheet mechanism may be pervasive.

2.2 Price at Date t and Crisis

Let us analyze the margin constraint in (1) further. Define,

$$l_t = 1 - \theta_t \tag{4}$$

as the amount of asset liquidated by a hedge fund at date t that does not receive a shock. As noted earlier, a fund that receives a shock liquidates one unit of the asset. If constraint (1) does not bind then $l_t = 0$, while if the constraint binds, substitute to find:

$$l_t = 1 + \frac{1}{m} \left(d_s - P_t^\omega \right). \tag{5}$$

Liquidations increase as the price falls and leverage (d_s) rises, capturing the balance sheet effect I have alluded to. The required margin m has two effects on liquidation. First, since d_s is always less than P_1^ω, increasing m increases liquidations. This is also apparent by inspecting the capital constraint (1) where raising m tightens the constraint. Second, from (5) we see that raising m decreases the sensitivity of liquidations to price conditional on the constraint binding. This is also intuitive from (1): if the constraint is binding, a fall in w_t tightens the constraint less when m is large.

In state $\omega = G$, total liquidations across the hedge funds are,

$$L_t^G = l_t$$

(which may be zero if $l_t = 0$). In state $\omega = B$, total liquidations are,

$$L_t^B = \frac{1}{2}(l_t + 1).$$

I assume that there are other potential buyers ("deep pockets") who can absorb these liquidations. Denote $P_t(L)$ as the demand function from these buyers. If $L_t = 0$, the price is $P_t(L = 0) = \bar{P}$, where $\bar{P}$ may be thought of as the long-term or fundamental value for the asset. If $L_t > 0$, the price falls below $\bar{P}$, indicating that there are a limited number of such buyers (or they themselves have limited funds).[7]

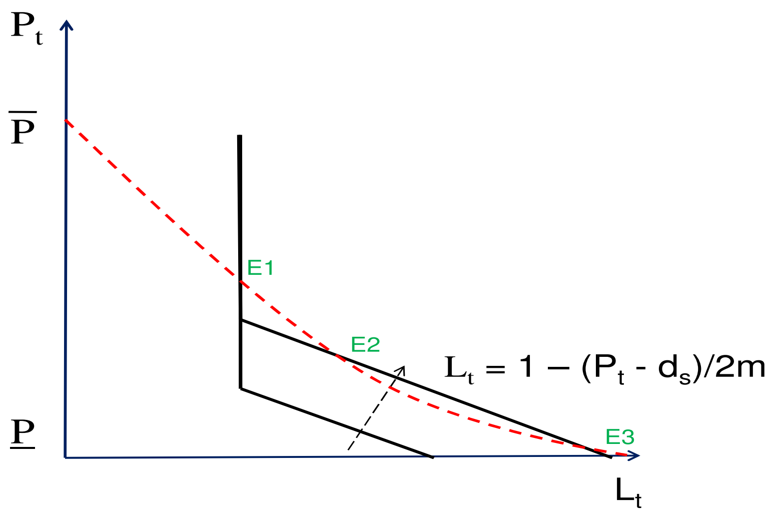

Figure 1: Liquidation Equilibria

The figure represents the equilibrium determination of P_t^B, the price in the bad state. Price is on the Y-axis and quantity liquidated on the X-axis. The negatively sloped curve indicates a demand function from the deep-pocket investors. The vertical-then-negatively sloped line is the hedge fund liquidation function, pictured for a low value of d_s and a high value of d_s.

Figure 1 illustrates an example of the equilibrium price determination for the B state. The price is on the Y-axis, while the quantity liquidated is on the X-axis. The demand function from deep-pocket investors

[7]The price function also satisfies, $P_t(L) > \underline{P} > 0$, indicating a positive lowest possible price.

is represented by the dashed curve. The aggregate liquidation function, L_t^B is pictured as the vertical-then-sloped line. The vertical segment reflects the case of exogenous liquidation where one-half of the funds have to liquidate. If price falls low enough so that $l_t > 0$, then there is also endogenous liquidation, which increases as the price falls.

If d_s is low, then the only equilibrium is at point $E1$. The exogenous liquidation shock causes the price to fall. If d_s is large enough, then it is possible for the equilibrium to involve endogenous liquidation – this is the sloped segment of the liquidation function. In the region in which there is endogenous liquidation, the increased d_s increases liquidation for every given price. Hence the liquidation function shifts upwards, when d_s is larger.

The figure presents three possible equilibria for the high d_s case. The exogenous liquidation equilibrium of $E1$ still exists. Equilibrium $E2$ is a moderate liquidation equilibrium where the price falls and the hedge funds liquidate some of their holdings. Equilibrium $E3$ is the severe liquidation equilibrium: low prices and large liquidations. In both $E2$ and $E3$ if agents expect prices to be low, they liquidate positions and push prices down. Note that of the two liquidation equilibria, $E2$ is an unstable equilibrium (i.e. any perturbation of prices or quantities moves the equilibrium to either $E1$ or $E3$), while $E3$ is the stable liquidation equilibrium.

The "crisis" in the model is represented as equilibrium $E2$ or $E3$. In these equilibria, the exogenous liquidation needs interact with a weak balance sheet (i.e. high pre-existing debt) and lead to endogenous liquidation and low value of P_t^B. It should be obvious that in state G, the price is $\bar{P}$ since $l_t = 0$. It is true in the model that P_t^B falls below $\bar{P}$ even in equilibrium $E1$, but I will not think of this as a crisis equilibrium since it is purely due to the exogenous liquidation shock.

2.3 Amplification of Shocks in State B

The model also illustrates an amplification mechanism in the B state. Figure 2 redraws the equilibrium for an alternative possible liquidation function, where the function is sloped in a manner that there is a single equilibrium. The rise in d_s moves equilibrium from $E0$ to $E1$. The comparison between $E0$ and $E1$ reveals that there may be a large change in price and quantity. In this sense, a potentially small change in d_s can lead to an amplified effect on prices and quantities. More generally, around the equilibrium $E1$, any shock (i.e. exogenous liquidation) that perturbs either curve has large effects on the equilibrium price and quantity since both curves are negatively sloped. This latter point underscores how the balance sheet constraint can lead to an amplification mechanism.

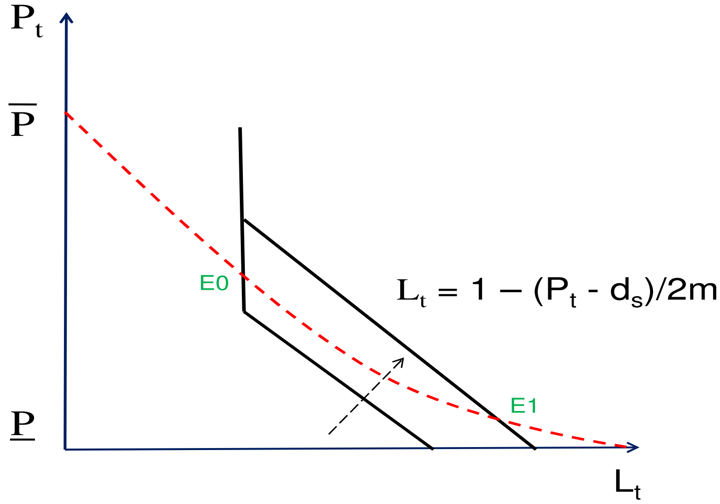

Figure 2: Amplification

The figure represents the equilibrium determination of P_t^B, the price in the bad state. Price is on the Y-axis and quantity liquidated on the X-axis. The negatively sloped curve indicates a demand function from the deep-pocket investors. The vertical-then-negatively sloped line is the hedge fund liquidation function, pictured for a low value of d_s and a high value of d_s.

Finally note that in comparing Figures 1 and 2, the liquidation functions have a different slope. A given change in price leads to larger change in liquidation in Figure 1 compared to Figure 2. The stronger liquidation effect leads to multiple equilibria. In this sense, the multiplicity in Figure 1 is just the extreme case of a large multiplier, and the more generic result of the model is shock amplification.

2.4 Related Amplification Mechanisms

The feedback loop between the asset market and balance sheets illustrated by the model has been explored in different contexts within the literature.

As noted earlier, the m of the model can be related to Kiyotaki and Moore's (1997) analysis of credit cycles. In that paper, a borrower debt-finances an asset purchase, providing an equity downpayment measured by m. Thus, the borrower carries leverage proportional to $\frac{1}{m}$ (m is to be thought of as a small number). A fundamental shock causes asset cash-flows to fall, causing the borrower's equity to fall more, given high leverage. The borrower's investment capacity going forward falls, which leads more of the asset to be owned by a second-best user. The value of the asset to the second-best user is less than that of the constrained borrower, causing asset values to fall, reinforcing the spiral. The Kiyotaki and Moore analysis shows how leverage can lead to a large balance sheet amplifier.

In Brunnermeier and Pedersen (2008), m is a margin requirement that depends on expected market price volatility, which, in equilibrium is a function of the actions of the constrained agents. They derive a crisis equilibrium in which volatility rises, causing m to rise, triggering asset sales and further increases in volatility. Thus their model shows how margins and volatility are related through what they label to be a "margin spiral." Vayanos (2004) presents a related analysis where the investors in a hedge fund withdraw money if volatility rises. Vayanos' model is fully dynamic which helps to understand the behavior of a risk premium on volatility innovations.

In He and Krishnamurthy (2008ab), m parameterizes an equity capital constraint. It measures how much equity outside investors are willing to provide to a hedge fund given the hedge fund manager's own equity investment in the fund. The hedge fund is assumed to invest in a risky asset that requires the investment expertise of the hedge fund manager. Moreover, there are only a limited number of hedge fund managers in the economy. Losses in the hedge fund trigger equity outflows that reduce the amount of capital the manager controls, causing the hedge fund to sell some assets. When such losses occur across the entire hedge fund sector, the potential buyers (i.e. other hedge funds) themselves are constrained. They have to buy assets using less capital. To induce them to do so, asset prices fall and risk premia rise. The He and Krishnamurthy analysis shows how risk capital and risk premia are related through a balance sheet amplifier.

There is also work in a multiple asset setting in which the feedback loop can be used to explain contagion effects. Kyle and Xiong (2001) is representative of this work. The models in this branch of the literature present the result that a shock in one market tightens balance sheet constraints and causes liquidations and falling asset prices in another market.[8]

Somewhat further from my model, but capturing a similar feedback is the work of Garleanu and Pedersen

[8]In all of the papers I have mentioned, it is because assets are "marked to market" that there is a feedback loop. Plantin, Sapra, and Shin (2008) build on this observation in analyzing the costs and benefits of "mark to market" accounting rules.

(2007). They develop a model in which a trader faces a constraint on how large an asset position it can take that depends on how quickly the trader can expect to sell the asset. Asset trade is modeling in a search framework. Thus, loosely speaking, m depends on the expected search time for a trader. They show that it is possible that a tighter m constraint reduces search times in the market, and feeds back into a further tightening of the m constraint.

Finally, the literature on banking starting with Diamond and Dybvig (1983) describes how maturity mismatch can underly an amplification mechanism. For example, Allen and Gale (2005) and Diamond and Rajan (2005) present models in which a bank is funded by short-term demandable deposits and holds long-term assets whose price is determined in a market equilibrium. There is a feedback loop between bank runs, asset liquidation, and lower asset prices.

2.5 Crisis Policy

The multiple liquidation equilibria as pictured in Figure 1 is a coordination failure and can motivate central bank intervention. There are a number of ways to implement policies to rule out the liquidation equilibria $E2$ and $E3$. Here I discuss three possibilities that have some context in the current crisis.

1. *Asset Purchase*: The Federal Reserve has been active in purchasing mortgage-backed securities in 2008 and 2009, citing unusually depressed market prices.[9] Many observers have argued for a more formal central bank role as a "market-maker of last resort" in secondary markets (Buiter and Sibert, 2007). Caballero and Kurat (2009) recommend that central bank policy should take the form of downside insurance. If prices fall below some level, the central bank commits to purchasing assets at that price (or insures asset-holders against losses in such a price decline).

   We can see the effect of such a policy within the model. Suppose that the central bank commits to purchasing liquidated assets at a price P^* just above P^{E2}. Then, the effective demand function, now from both deep-pocket investors and the central bank, has a floor at P^*, thereby ruling out the $E2$ and $E3$ crisis equilibria.

2. *Discount Window Lending*: The Federal Reserve has offered to finance the asset holdings of commercial and investment banks at margin requirements far lower than is offered in private-sector transactions. The clearest case of this is lending against subprime mortgage-backed securities, where the Discount

[9] See http://www.federalreserve.gov/newsevents/press/monetary/20081125b.htm.

Window lends at 0.90 to the dollar, while the private market has essentially shut down. Consider again the constraint (1). The constraint requires that a hedge fund put up a margin of $m\theta_t$ in order to hold θ_t units of the asset. We can readily interpret this constraint to mean (as I have when discussing the model in terms of Kiyotaki and Moore, 1997) that lenders are willing to provide $(1-m)$ of financing collateralized by one unit of the asset if the hedge fund puts up m of its own resources. Thus, in my discount window example, the 0.90 translates into an m of 0.10.

Suppose that the central bank commits through the discount window to offer financing at a margin requirement $m^* < m$ if the price falls below P^*. Then, in the region where $P_t < P^*$ (for P^* just above P^{E2}), endogenous liquidation is positive if,

$$l_t = 1 - \frac{1}{m^*}(P_t - d_s) > 0.$$

In terms of P_t, the price must be low enough that,

$$P_t - d_s < m^*$$

in order to fall into the region of endogenous liquidation and crisis. By lowering m^*, the policy lowers the price below which endogenous liquidation is triggered. Indeed if $m^* = P^* - d_s$, the central bank can rule out the crisis equilibria. The policy has the effect of shifting the liquidation function downwards in Figure 1.

3. *Equity Injection*: The Treasury has been active in injecting equity into the financial sector. Suppose that the government invests e more capital into hedge funds if $P_t < P^*$. The benefit of such policy is that it directly relaxes the constraint (1) by raising w_t. In the region where such injections take place, endogenous liquidation is,

$$l_t = 1 - \frac{1}{m}(P_t + e - d_s).$$

It is apparent that increasing e works exactly like decreasing d_s. As in Figure 1, a decrease in d_s shifts downwards the liquidation function and thereby rules out the crisis equilibria.

In a more dynamic formulation, one can also consider a debt-for-equity swap. That is imagine a date just prior to date t, where the government forces some of the debt-holders to accept equity claims in place of their debt claims. This policy reduces d_s, so that at date t, the liquidation crisis may be avoided. The next section develops a closely related point by considering debt choices at date s.

2.6 Ex-ante Policy

The balance-sheet model opens the door to studying ex-ante policy. That is, the possibility of multiple equilibria at date t in the model indicates that there is an externality among agents. If we focus on date $s < t$, then the ex-ante debt choice affects the strength of the date t externality. As I will show, this logic implies that generally the date s debt choice of the hedge fund is inefficient. The result is one of the intellectual underpinnings of prudential capital or liquidity requirements, or more generally, regulation of the balance sheet liquidity of the financial sector.

The externality is present in both the multiple equilibria and amplification cases presented. To simplify exposition, I focus on the amplification case presented in Figure 2, equilibrium $E1$. With probability $1 - \Phi$ the G state realizes and the price is $\bar{P}$, while with probability Φ the B state realizes and the equilibrium is at $E1$.

I carry out the following experiment. Suppose that a hedge fund increases the date s debt financing of d_s by a small amount and reduces the equity contribution by the same small amount so that the date s asset position is unchanged. I compute the ex-ante valuation of this change for a single fund and contrast this number with the same computation when the entire hedge fund class increases d_s. As one would conjecture, both of these valuations are negative since increasing d_s increases endogenous liquidations. The interesting result is that generally the private cost of debt is smaller than the social cost, suggesting that agents may over-leverage in equilibrium. Note that my experiment is silent on the benefit of debt over equity financing. Rather than getting into a model of corporate financing to derive this advantage, I will imagine fixing this benefit and holding it constant across the two computations.

Consider first the single agent computation. A hedge fund's expected value from asset holding, given d_s and P_t^ω, is:

$$V^P = (1 - \Phi)\bar{P} + \Phi\left((1 - L_t)\bar{P} + L_t P_t^B\right)$$

The first term in this expression reflects the payoff in the G state in which case the asset is held to realize the fundamental value of $\bar{P}$. The second term is the payoff when there are L_t assets liquidated in the $E1$ equilibrium.

Differentiating this expression, I find:

$$\begin{aligned} \frac{\partial V^P}{\partial d_s} &= -\Phi(\bar{P} - P_t^B)\frac{\partial L_t}{\partial d_s} \\ &= -\Phi(\bar{P} - P_t^B)\frac{1}{2m}, \end{aligned} \tag{6}$$

where the second line follows from expression (5). The cost of higher leverage is that the asset may be liquidated early at price P_t^B rather than held to maturity to yield a payoff of $\bar{P}$.

For the entire hedge fund class, the computation needs to account for the fact that P_t^B is affected by the choice of d_s:

$$V^S = (1-\Phi)\bar{P} + \Phi\left((1-L_t)\bar{P} + L_t P_t^B(L_t)\right).$$

Thus,

$$\frac{\partial V^S}{\partial d_s} = -\Phi(\bar{P} - P_t^B)\frac{1}{2m} + \Phi L_t \frac{\partial P_t^B}{\partial L_t}\frac{\partial L_t}{\partial d_s}. \tag{7}$$

From Figure 2, we see that increasing d_s shifts the liquidation function upwards and lowers P_t^B (i.e. increases liquidations). Hence,

$$\left|\frac{\partial V^S}{\partial d_s}\right| > \left|\frac{\partial V^P}{\partial d_s}\right|,$$

where these derivatives are negative.

Intuitively, the social cost of debt is higher than the private cost of debt because a single hedge fund does not take into account that its increasing d_s makes the fund have to liquidate more asset at date t, pushing prices lower at date t, which in turn results in greater liquidations by other hedge funds. Since the market price is endogenous at date t to the trades of the hedge funds, the trading externality that is present at date t translates into a financing externality at date s.

Thus a central bank policy that restricts date s leverage, or imposes a minimum equity capital requirement, can improve welfare. These are common regulations for commercial banks, and some of the recent policy discussion regards extending these regulations to other parts of the financial sector including hedge funds and investment banks.

In more general settings, the externality leads to "underinsurance" against the crisis equilibrium – the leverage externality of the current model is just one instance of underinsurance. Consider for instance a model in which there are many states at date t, in which in only some of the states is equilibrium at $E1$; in other states the equilibrium is either at $\bar{P}$ or at the vertical segment of the liquidation function. In such a model, the optimal policy will call for agents to have more liquid balance sheets (i.e more w, less d) in only the crisis states. Thus more generally the policy I have outlined concerns the risk management of balance sheet liquidity. The externality leads agents to make ex-ante asset and liability choices that leaves them with a less liquid balance sheet in crisis states.

Caballero and Krishnamurthy (2003) study the underinsurance externality in the context of emerging market crises and discuss firms' financing choices over domestic and foreign currency debt arguing that firms will undervalue the insurance benefit of denominating debt in domestic currency. Gromb and Vayanos (2002) study a similar externality in a dynamic model of collateral constrained arbitrage and show that the arbitrageurs trade too early in trying to profit from the arbitrage opportunity. Allen and Gale (2004) discuss the source of the inefficiency in banking/financial markets models. The inefficiency of equilibrium in these papers is an example of a more primitive result derived by Geanokoplos and Polemarchakis (1986) on the generic inefficiency of equilibrium in incomplete markets.

Finally, strictly speaking if I define welfare in the current model as the sum of hedge fund/household and deep-pocket investor utility, then since liquidations just leads to transfers, the date s debt choice does not affect welfare. It is straightforward to consider setting where quantities (i.e. real investment) adjusts and describe ex-ante policies that are Pareto improving. See Caballero and Krishnamurthy (2003, 2004) or Lorenzoni (2008) for a full treatment of ex-ante policies.

3 Amplification through Uncertainty

In early 2007, banks were well capitalized and flush with cash. Similar statements of health could be made about most of the key pieces of the financial sector. In terms of the model just discussed, $w - d$ was high. From the vantage of the balance sheet liquidation mechanism, these benign initial conditions make it hard to understand the extent of the recent crisis.

I argue in this section that an important amplification mechanism in the recent crisis has to do with lack of knowledge and uncertainty. Investors had rapidly adopted a financial innovation – the credit market structures – with which they had a limited history. When AAA subprime tranches suffered losses, investors realized that they had not understood the securitized credit structures they had purchased. Investors were not surprised that high-risk homeowners defaulted on some loans; rather, they were surprised that such defaults had a material effect on the values of the most senior of the tranches backed by pools of subprime mortgages. Moreover, given that a myriad other credit products - not just mortgage – had been structured in much the same way as subprime investments, investors' model-uncertainty was across the entire credit market.

Thus, the small cash-flow shock of subprime defaults resulted in a large shock to investors' uncertainty.

Moreover there was contagion across the entire credit market due to investors' model uncertainty. The response of investors to their uncertainty was to disengage. Investors went back to the drawing board to formulate new models. In the meantime, given that they did not have a clear understanding of events, they took decisions to protect themselves against worst-case scenarios on the risks that they did not understand. The result of all of this disengagement was a loss of liquidity, with many attendant effects.

Investors' dramatic disengagement and emphasis on protecting against a worst-case event is hard to capture within a standard model of decision making. In the standard model, agents consider all possible models — for example, models in which AAA tranches are not risky and those in which they are risky — placing probabilities on each of the possible models, and then making decisions that average over the models in a Bayesian fashion. The shock (i.e. AAA defaults) leads agents to adjust their model-probabilities, increasing their weight on the model in which AAA tranches are risky. Of course such a reassessment leads to lower prices on the AAA tranches. But, it does not lead to disengagement nor the worst-case decision rules that have been witnessed recently.[10]

The main difficult with the standard model in capturing these events is that under the Savage axioms for decision-making, model uncertainty and risk regarding cash-flows are treated the same way. Indeed, leaving aside the subprime example that I have given, there is a long tradition in Economics dating back to Knight (1921) that recognizes that risk and uncertainty provoke different behavioral responses. The point is most clearly made in the Ellsberg (1961) paradox. Giving people choices between gambles where some gambles had clearly specified odds, while others did not, Ellsberg found that people consistently avoided the gambles with unknown odds. In fact, Ellsberg found that one could combine the known and unknown gambles in ways that showed that people violated the Savage axioms.

Beginning with Gilboa and Schmeidler (1988), there have been a number of papers aimed at developing a theory of decision-making that distinguishes between risk and uncertainty and is consistent with the behavior noted by Ellsberg. Consider a decision problem where a state $\omega \in \Omega$ will be realized tomorrow. The probability distribution over the states is denoted by π. An agent makes a decision $d \in D$ today that results in utility $u(c(\omega, d))$ in state ω. The standard Expected Utility representation of this decision problem

[10] Routledge and Zin (2005) argue similarly that the trading-halts (near zero trading volume) and disengagement we observe during financial crises are an important reason to think that these events are about Knightian uncertainty. Routledge and Zin develop a model in which uncertainty leads to a trading hald and widening of bid-ask spreads.

is that the agent solves,

$$\max_{d \in D} \; E_\pi[u(c(\omega, d))].$$

Suppose however that agents are uncertain over the probability distribution π. In particular, suppose that this uncertainty is that agents only know that $\pi \in \Pi$. Then, Gilboa and Schmeidler's Maximin Expected Utility representation of Knightian uncertainty aversion is,

$$\max_{d \in D} \; \min_{\pi \in \Pi} \; E_\pi[u(c(\omega, d))].$$

The "min" operator is the key here: agents use a worst-case for the uncertain probabilities π when making their decision.

In the subprime example, one may consider that agents had a model $\pi \in \Pi_0$ in mind at the beginning of 2007. The default events led them to become uncertain, so that they considered a larger class of models Π_1 (e.g., $\Pi_0 \subset \Pi_1$). Although the Gilboa and Schmeidler (1989) theory is not dynamic and therefore does not explain how agents' priors are updated, there has been subsequent work in the decision theory literature that does (see Hanany and Klibanoff, 2007, for discussion of this research).

This section presents extensions of the model to incorporate Knightian uncertainty, in ways guided by the recent credit crisis, and shows that the model can well capture recent events. I then turn to a discussion of some other historical crises in light of the uncertainty model, arguing that the subprime case illustrates a more general pattern present in other financial crises. Finally, I discuss policy in the uncertainty model and compare it to policy in the balance sheet liquidation model.

3.1 Crisis at Date s

The uncertainty channel that I explore is a dynamic one: it works through the effects on current decisions of anticipating future liquidity problems. For the purpose of modeling, I shift the focus of the model from date t back to date s. Agents at date s are uncertain over outcomes at date t and this may lead to liquidity problems at date s. That is, date s is no longer a benign initial condition of the previous section's analysis, but is the "crisis" date itself. I am centrally interested in agent decisions and the asset price at date s.

I set d_s to zero and remove the leverage channel of the previous section. I instead analyze a new concern that stems from anticipating liquidity supply problems at date t. Suppose that a "liquidity provider" stands-by to purchase the asset if investors wish to liquidate at date t. After describing the model, I provide some examples of such a liquidity provider.

The liquidity provider has resources of L — cash, or some other liquid medium — to back up the commitment. My key assumption is that the supply of liquidity is limited. If liquidations are sufficiently small, the liquidity provider buys at price $\bar{P}$. However, if liquidations are large enough, the price falls so that,

$$P_t = \frac{L_t}{L};$$

that is, the L resources are divided evenly to all liquidators.[11]

I consider a richer specification of the date t liquidity shocks. There are two classes of hedge funds, A and B, each in unit mass. Each of these classes may receive an exogenous liquidation shock at date t with probability ϕ. Thus, the states at date t are $\omega \in \{No, A, B, AB\}$, with probabilities $\{(1-\phi)^2, \phi(1-\phi), \phi(1-\phi), \phi^2\}$.

I assume that L satisfies:

$$\bar{P} < L < 2\bar{P}.$$

Thus, in the cases of no or one shock, the intermediary has sufficient L to redeem shares at a price of $\bar{P}$, while in the case of both shocks, the intermediary redeems shares at the price,

$$P_t^{AB}(L) = \frac{L}{2}.$$

Then the price of the asset at date s is $P_s = E[P_t]$, or,

$$P_s = \bar{P} - (\bar{P} - L/2)\phi^2. \tag{8}$$

We can think of $(\bar{P} - L/2)\phi^2$ as the liquidity discount on the asset. The anticipated liquidation shocks leads to a crisis discount at date s itself. Clearly this discount is decreasing in L.

Here are some examples of liquidity providers with limited liquidity in the current context. Commercial banks provide backup commitments to asset-backed facilities; i.e. if investors do not roll over their commercial paper loans to the facility, the commercial bank provides the loan. This type of liquidity provision arrangement arises both in the asset-backed commercial paper (ABCP) market as well as in sponsored investment vehicles (SIVs) (see Acharya and Schnabl (2009) and Gorton (2008) on commercial banks and their

[11] This formulation, in terms of a liquidity provider, provides one way to think about the $P_t(L)$ function of the previous section. That is, the price is the result from selling L_t shares to an investor with total resources of L. Also note that this formulation differs from the sequential service constraint of Diamond and Dybvig (1983). In that paper, the first liquidators to arrive at the bank receive more money than later liquidators – in my formulation, all liquidators are treated equally.

SIVs). It follows, as in the model, that if investors forecast that a sponsoring commercial bank will suffer losses causing L to fall, P_s will fall, corresponding to the rise in spreads on ABCP.

Consider another example. Hedge funds contract credit lines from commercial banks to provide them with emergency liquidity. Suppose that the liquidity provider is a commercial bank with limited L. Hedge funds A and B purchase credit lines to protect against their liquidity shocks. If both hedge funds receive liquidity shocks, they exhaust the commercial bank's liquidity, which may cause them to liquidate the asset in order to offset the liquidity shock. The anticipation of this scenario causes P_s to be low.

3.2 Counterparty Risk

The shock probabilities for each class of investors, A and B, is ϕ. I have thus far discussed the shocks as if they are known to be independent, but suppose that the shocks have correlation of ρ, possibly different than zero. Moreover, suppose that agents are *uncertain* over the value of ρ, knowing only that $\rho \in [-1, +1]$.

The problem of an investor at date s is to decide how much to pay for the asset, given the agent's probability of liquidation and the promised price-support. Uncertainty enters into this decision because the agent knows that the liquidity provider has limited resources, and if shocks to both A and B occur at the same time, it will not be able to provide full price support.

This way of introducing uncertainty captures "counterparty risk." Will the liquidity provider be able to deliver on its commitment when needed, or will other shocks deplete its liquidity so that it (partially) defaults? In the current context, the concern may be will the commercial bank suffer losses on its subprime investments, causing L to fall. Alternatively, the concern may be that hedge fund A worries that hedge fund B will suffer losses and need liquidity, depleting the liquidity of a commercial bank that has provided a credit line to both hedge funds. Note that even if A can accurately assess his own shock probability to be ϕ, the modeling is that he may be uncertain about the shock distribution for B. This is another way of thinking about counterparty risk – i.e., A's concern is will risks to other agents end up affecting him?

It is obvious that in the simple setup the "worst-case" for the agents is if $\rho = +1$. The maximin decision rule is to purchase the asset assuming that the counterparty risk is the highest. The date s price is then

$$P_s = \bar{P} - (\bar{P} - L/2)\phi. \tag{9}$$

Comparing this expression to that in equation (8), we see that uncertainty magnifies the importance of the liquidation event from order ϕ^2 to order ϕ.

3.3 Individual Exposure to Aggregate Risk

In the recent crisis, banks have been unsure of the extent of their own exposure to subprime and related credit risks. The problem stems from the complexity of these instruments. Different parts of banks have different risk exposures. Taking stock of all of this to provide an overall risk picture for a bank has taken time and proven difficult. The problem has been compounded because in many cases the markets for the relevant assets have become illiquid, making it difficult to measure market values.

On the other hand, it has been easier to estimate the aggregate losses stemming from subprime defaults. That is, beginning with the subprime borrowers, one can estimate default probabilities and recovery rates on default, and provide an upper bound on the subprime losses. Brunnermeier (2008) reports an over-estimate here of $500 bn. The uncertainty over the credit market structures is what has made it difficult to measure individual exposures to the aggregate risk.

Consider the following variation of the model. Suppose that at date t there are only two states, shock or no-shock (with probabilities ϕ and $1-\phi$). In the shock state, only one of either agents A or B receive a liquidity shock. Agents are uncertain over which agent will receive the shock. Denote ϕ_A and ϕ_B as the shock probabilities for A and B. Since only one of A or B will receive the shock,

$$\phi_A + \phi_B = \phi$$

However, suppose that A is uncertain over the value of ϕ_A. A only knows that $\phi_A \in [\phi/2 - K, \phi/2 + K]$ ($K \leq \phi/2$). The treatment of B is symmetric.[12]

It is easy to see how the uncertainty affects the date 0 decision. The worst-case for the agent is if their shock probability is $\phi/2 + K$. Then the agents price the asset so that,

$$P_s = \bar{P} - (\bar{P} - L/2)(\phi/2 + K).$$

Uncertainty reduces the asset price, increasing the importance of the liquidation state. (I have normalized things by assuming that the intermediary has $L/2$ units of liquidity, since liquidity needs have been halved relative to the previous extension.)

[12] In this model, one solution to the uncertainty problem is for A and B to cross-insure each other. Both buy insurance against their own shock state and sell insurance against the others' shock state. I am assuming that markets are incomplete so that this trade is not possible. Caballero and Krishnamurthy (2008) develop a related model based on uncertainty over idiosyncratic exposures to aggregate shocks where markets are complete, yet the equilibrium is qualitatively similar to the one described here. The main modeling difference is that in Caballero and Krishnamurthy, the model is completely symmetric – there is no distinction between "A" and "B" types.

3.4 Wasted Liquidity

Thus far I have discussed how increases in uncertainty lead to a fall in the asset price at date s. This section discusses a second effect of increases in uncertainty. Increased counterparty risk typically triggers demands to create a "safer" contract. Agents require more collateral from counterparties. A hedge fund pulls its business from a weaker bank and recontracts with a safer bank. When triggered by uncertainty, the demand for safety can lead to wasted liquidity, as I explain next.[13]

To fix ideas, let us focus on the hedge fund/credit line interpretation of the model. Moreover, suppose that the liquidation shocks occur not at time t, but at some time *between* s and t. If hedge fund A receives such a shock, it immediately requires resources and draws down its credit line from the liquidity provider. Hedge fund A may receive a liquidation shock between s and t, and then, possible, hedge fund B may receive another shock. As before, there are four possible histories at date t; $\omega \in \{No, A, B, AB(BA)\}$ with probabilities $\{(1-\phi)^2, \phi(1-\phi), \phi(1-\phi), \phi^2\}$.

Since now shocks arrive between s and t, and liquidity is needed at the time the shock arrives, liquidity must be provided at a time before t. Importantly, the bank cannot wait until time t to decide how much of its L to allocate to each fund (as in the previous examples). Define the pair (L_1, L_2) as the liquidity provided to the first and second shock, respectively. We can imagine that the credit line specifies ex-ante a pair (L_1, L_2).

With this change in the modeling, a credit line arrangement has to be optimized over L_1 and L_2, subject to $L_1 + L_2 = L$. But, the sequential shock structure in the economy immediately implies that any optimized pair (L_1, L_2) must have the property that

$$L_1 > L_2.$$

That is, since conditional on one shock arriving, the probability of the second shock arriving is strictly less than one, it is better to provide more resources to the first shock than the second shock. Given risk neutrality in all agents' preferences, it is optimal to set the ratio $\frac{L_1}{L_2}$ equal to $\frac{1}{\phi}$, unless such a solution involves $L_1 > \bar{P}$. If ϕ is sufficiently low, then the solution is to set $L_1 = \bar{P}$ and $L_2 = L - \bar{P}$.

Consider this latter case; ϕ is sufficiently small that,

$$L_1 = \bar{P} > L_2 = L - \bar{P}.$$

That is, it is optimal to set L_1 sufficiently high that the hedge fund with the first shock receives enough

[13] The section draws heavily from Caballero and Krishnamurthy (2008).

funds to fully absorb its liquidation shock at price $\bar{P}$, leaving less than $\bar{P}$ for a potential second hedge fund shock.

The date s asset price is,

$$P_s = \bar{P} - \phi^2(\bar{P} - L/2)2.$$

As before, there is a liquidity discount.

Now, suppose we introduce uncertainty into this environment. A is uncertain over the value of ϕ_B, considering values of $\phi_B \in [\phi - K, \phi + K]$ ($K \leq \min[\phi, 1 - \phi]$). The treatment of B is symmetric. That is, each hedge fund is uncertain over the other fund's shock probability.

If K is sufficiently large that the $\phi + K$ is close to one, then A will be concerned that B will receive the liquidity shock first, depleting the bank's liquidity, leaving too little liquidity for A (i.e. $L_2 < L_1$). Given this fear, the price of the asset will be,

$$P_s = \bar{P} - \phi(\bar{P} - L/2)2.$$

As before, the uncertainty concern reduces the asset price, magnifying the importance of the liquidation event from order ϕ^2 to order ϕ.

There is a new result that emerges from the sequential-shock model. Consider that A (and B) will prefer the following alternative credit line arrangement: The liquidity provider writes two independent contracts, each collateralized by $L/2$ units of liquidity. Contract A promises upto $L/2$ liquidity to hedge fund A regardless of what happens to B, and likewise for contract B.[14]

This implementation disentangles the A shock from the B shock, removing counterparty risk. Effectively each hedge fund disengages from the risks that he does not understand and guarantees a known amount of liquidity for himself. The hedge funds then price the asset at date s requiring only the knowledge of their own shock-probability. Hence,

$$P_s = \bar{P} - (\bar{P} - L/2)\phi.$$

For

$$\bar{P} - L/2 < 2\bar{P} - L,$$

or,

$$L < 2\bar{P},$$

[14] This two contract implementation can also be thought of as setting $L_1 = L_2$.

which is the maintained assumption, the liquidity discount is smaller under the over-collaterization arrangement. From a hedge fund's standpoint, removing counterparty risk through over-collateralization provides a better outcome than contracting with a liquidity provider and running the risk that the provider will default.

The over-collateralization scheme though comes at a cost. Part of the liquidity provider's resources of $L/2$ are wasted in the equilibrium because there are states at date t, the ones in which only one of A or B receive the liquidation shock, in which the liquidity of the non-shock contract goes unused. Investors' uncertainty causes the effective supply of liquidity to contract.

Financial crises are not typically about an aggregate shortage of resources, but rather about the distribution of these resources. Resources that could be valuably deployed stay on the sidelines. For instance, in the recent credit market events, regulators have been concerned that many banks have been hoarding their liquidity, causing the money market to be illiquid. Uncertainty-induced liquidity waste is one way to model these outcomes.

3.5 History and Financial Innovation

The preceding extensions illustrate how a rise in Knightian uncertainty can lead to a lack of liquidity.[15] My modeling choices in the extensions are guided by the subprime crisis. In this section, I turn to other historical crisis episodes, interpreting these events in light of the uncertainty model.

The uncertainty model is most suited to environments where market participants have had a limited experience in dealing with a particular asset. These circumstances provide fertile ground for "unusual" events – such as the losses on AAA rated subprime tranches. That is, it is likely that something occurs that is at odds with market participants' models of the world. Knightian uncertainty and market illiquidity follow naturally.

Consider in particular the following narrative of a financial innovation. A successful financial innovation is a product that meets a market demand and is therefore taken up widely. In the subprime case, securitized

[15] The uncertainty model may remind the reader of an adverse selection model. That is, consider a model in which an investor is worried that he may be purchasing the worst asset in a pool (i.e. the "lemon"). This is similar to the uncertainty averse agent who is worried about a worst-case scenario when investing. Indeed, some observers have argued that adverse selection problems have played an important role in the current mortgage crisis. These models are also similar in that the behavior of agents is due to lack of information. However, an important implication of the uncertainty model is that it suggests that crises are most likely to arise on new asset classes. An adverse selection problem can arise on any asset, new or old. The history I review in this section thus seems like better motivation for the uncertainty model.

credit products have come to proliferate the market in the short space of five years. Thus, by its very nature, a successful financial innovation provides market participants with only a short history and there will be outcomes that people do not expect. The subprime case clearly fits this narrative, but consider some other historical episodes.

In 1970, the Penn Central Railroad defaulted on $82m of prime-rated commercial paper. The commercial paper market at the time was not as mature as it is today. It had developed rapidly through the 1960s to meet growing corporate borrowing needs. However, ratings were not fine tuned and back-up liquidity facilities, which are standard practice today, did not exist. When the default occurred, it spooked money-market investors. These investors went back to the drawing board to re-evaluate their credit models and ratings guidelines. The result was disengagement. Investors stopped buying commercial paper completely. Over time, and with the Fed intervening by encouraging banks to buy commercial paper, the market normalized.

Contrast this event with the 1997 Mercury Finance - another commercial paper borrower – default on $500m of paper. The default was much larger in real terms than Penn Central and was similarly a surprise to the market. In contrast to the Penn Central case, there were no effects on the commercial paper market. The reason is that it quickly became clear that the default was a case of fraudulent accounting in Mercury Finance. The uncertainty element that had been important in 1970 was not present.

Another example to illustrate these points is the stock market crash of October 19, 1987. The new innovation in this episode was portfolio insurance strategies – that is, the synthetic replication of put options. This was a strategy that had become increasingly common among investors in this period. However, in 1987 it was unclear how widespread these strategies were and how financial markets would equilibrate in the presence of portfolio insurance strategies. The speed of the market decline on October 19 took everyone by surprise. Market makers widened their bid-ask spreads and other key market players pulled out of the market completely. The result was a lack of liquidity. Many observers point to the option-replication drive sales into an illiquid market as being an important factor in the market crash. Today, these types of replications strategies are common and well understood by all market participants.

My last example is the hedge fund crisis of the fall of 1998. In this scenario, hedge funds were still a relatively new and opaque financial vehicle. Assets under hedge fund management had grown from around $10 bn in 1991 to $80 bn in 1997 (still far less than the trillions under management today). In the fall of 1998, even sophisticated market participants such as Long Term Capital Management were taken by surprise by the unprecedented comovement of Russian government bond spreads, Brazilian spreads, and

U.S. Treasury bond spreads. The standard risk management models that hedge funds used were no longer applicable (Scholes, 2000). The result was that financial market participants searched for new models and made decisions based on worst-case scenarios. We now know that hedge funds had similar strategies and had filled up a similar asset space, and that this was the source of the correlations. Indeed risk management strategies post-1998 explicitly account for high-correlation illiquidity events. But at the time neither hedge funds nor their creditor banks understood this point. The result of this uncertainty was illiquidity and crisis.[16]

The preceding discussion covers three of the major financial crises experienced in the U.S. over the last 50 years.[17] Each of these episodes is associated with a financial innovation, and occurred at a time when market participants had only a limited history within which to understand financial developments, suggesting that Knightian uncertainty is an important factor in many financial crises.

3.6 Policy

The crisis in the model is at date s. It arises because agents anticipate liquidity problems at date t and adjust decisions at date s accordingly. Thus effective crisis policies in the model are ones that reduce agents' fears regarding liquidity problems at date t.

Here are two policies that have such a flavor. First consider the price-floor policy discussed earlier. Suppose that the central bank commits to purchase the asset if P_t falls below some $P^* > \frac{L}{2}$. This policy can have a large effect in the uncertainty model. In the counterparty risk example, the increase in P_s due to such a commitment is proportional to $\phi(P^* - L/2)$ in the uncertainty model, while in the no-uncertainty case it is proportional to $\phi^2(P^* - L/2)$. In the correlation risk example, the increase in P_s is proportional to $\phi/2 + K$, while in the no-uncertainty case, the increase is proportional to $\phi/2$.

A lender of last resort policy is also valuable in the uncertainty model. Consider that if the central bank commits to inject one unit of resources into the liquidity provider (increasing L) in the two-shock state (where both A and B receive a shock), this commitment can have a large ex-ante effect on the price P_s. The policy raises P_t in the two-shock state and thereby has an order of magnitude larger effect in the uncertainty case than the no-uncertainty case. In effect, the central bank delivers resources to the market in the states

[16] While in 1998 hedge funds were still a novel financial vehicle, the large reported losses of the Amaranth hedge fund in 2006 barely caused a ripple in financial markets.

[17] See Calomiris (1994) on the Penn Central default, Melamed (1998) on the 1987 market crash, Scholes (2000) on the events of 1998, and Stewart (2002) or McAndrews and Potter (2002) on 9/11.

that agents are most anxious about, which is why these policies have a large effect.

In addition to raising P_s, these policies have an effect on liquidity waste. Consider the effect of the central bank's promise to add one unit of liquidity to the liquidity provider in the context of the wasted liquidity example I have developed. With such a promise, each agent will be happy with a contract that delivers $\frac{L+1}{2}$ liquidity to that agent if he needs the liquidity. That is, each hedge fund will compute that the maximum credit line that the liquidity provider can promise, without any uncertainty concerns, is $\frac{L+1}{2}$. Now suppose that only one shock hits the economy and the central bank does not deliver the extra unit of liquidity to the liquidity provider. Note that even in this case, the hedge fund that is hit by the shock gets an extra $\frac{1}{2}$ of resources. The central bank's promised liquidity injection changes decisions and contracts at date s in a way that liquidity is more efficiently utilized. Caballero and Krishnamurthy (2008) develop this point more fully, discussing some of the welfare issues that arise when agents' preference do not satisfy the Savage axioms.

While crisis policy is similar across the uncertainty and liquidation model, my conjecture is that there is less scope for ex-ante balance sheet regulation in the model. In the liquidation model, the ex-ante policy is to reduce leverage. As I have noted, in a more sophisticated model this policy will be about incentivizing agents to improve risk management. Agents must increase the liquidity of their balance sheets only in the states of the world where a liquidity event will occur. We then have the following question. Does the central bank know which states are the uncertainty-crisis states? Consider that the central bank is in the same (or worse) position as the private sector in forecasting how a crisis on a financial innovation will unfold. Of course the central bank can require a blunt policy such as carry more liquidity/reduce leverage/reduce asset positions into *all* states of the world. But such a policy may be prohibitively costly since it distorts private sector actions in non-crisis states, and these states may be the more likely ones.

Instead, the logic of the uncertainty model suggests that regulations to limit the aggregate size of a financial innovation may be optimal. That is, if the CDO credit structures were as complex as they have come to be, but were in total only \$1 trillion rather than \$5 trillion, then the fallout from the uncertainty shock would have had far less impact on the economy. The model suggests that something analagous to a Tobin-tax, but directed only at financial innovations, may be an optimal policy response. This conjecture needs to be investigated more thoroughly.

4 Liquidity in a Crisis

Most observers use the phrase "lack of liquidity" to describe a crisis. Liquidity, unfortunately, is a word used to describe many different aspects of a crisis. This section discusses the different senses in which there is lack of liquidity in a crisis within the model I have presented. I relate the discussed notions of liquidity to the different ways in which liquidity is measured in empirical work.

In the models I have presented, the asset market is illiquid in the sense that the asset price falls below the long-run fundamental of $\bar{P}$. We can think of the spread $\bar{P} - P$ as a liquidity discount. For example, if the underlying asset in the model is a defaultable corporate or mortgage bond, then it easy to translate $\bar{P} - P$ into the spread between the yield on the bond and the yield on a Treasury bond. In many bond market crises, such spreads rise significantly.

The empirical literature in finance offers other ways to describe *asset market liquidity*, defined broadly as the ease with which an asset can be converted into a liquid medium such as cash or bank reserves. In a crisis, market participants find that their assets lose market liquidity. Potential trading partners are hard to find (Duffie, Garleanu, and Pedersen, 2005). Market-makers are reluctant to accumulate inventories and provide immediacy to investors (Weill, 2007). It is common in the market micro-structure literature in finance to measure market liquidity in terms of bid-ask spreads or price impact measures (Kyle, 1985, O'Hara, 1995, Chordia, Roll, and Subrahmanyam, 2000) or trading volume and volatility measures (Amihud, 2002, Acharya and Pedersen, 2005). A number of papers measure the resiliency of an asset – how quickly the asset price recovers following a large trade – by measuring the negative serial correlation in asset returns (Campbell, Grossman and Wang, 1993, Pastor and Stambaugh, 2003).[18]

Liquidity is also often used to describe the condition of a financial institution's balance sheet. For example, L is the cash-on-hand of the liquidity provider; more L means a more liquid balance sheet. Likewise the equity cushion of $w - d$ for the hedge funds is a measure of the hedge funds' liquidity. Note that while market liquidity describes a market equilibrium outcome, *balance sheet liquidity* describes the condition of a particular actor in the market.

Balance sheet liquidity appears commonly in the corporate finance literature. An institution is liquid – or not liquidity constrained – if its balance sheet contains predominantly cash-like or other easily saleable assets, and its liabilities are tilted away from a hard-claim like short-term debt, for which default may lead

[18] Pastor and Stambaugh (2003) further distinguish between market liquidity and market liquidity risk – with the latter carrying a risk premium on innovations to market liquidity.

to bankruptcy, and towards softer claims like equity. In this instance, balance sheet liquidity is high: if needed, the institution can repay all of its short-term debt and forestall bankruptcy. Empirical work in corporate finance often uses cash or leverage to measure balance sheet liquidity (see Kashyap and Stein, 1995, Gatev and Strahan, 2006, Adrian and Shin, 2008ab). A common theme in many accounts of crises is that institutions own long term assets, funded by short term debt, which results in a balance sheet with low liquidity (Diamond and Dybvig, 1983).

A drying-up of liquidity is also used to describe deteriorating external financing conditions. For example, imagine in the model that m, the margin requirement, was to rise in a crisis. That would mean that the lenders to the hedge fund raise their margin/collateral requirement and thereby tighten financing terms.

More broadly, the literature refers to deteriorating external financing conditions as a reduction in *funding liquidity*.[19] During crises, borrowers face higher costs in the loan market. A hedge fund that wants to borrow using financial securities as collateral (a "repo agreement"), faces higher collateral requirements (Brunnermeier and Pedersen, 2008, Gorton, 2008). Adrian and Shin (2008a) document that repo market volumes fall during crises. Unsecured lending, backed broadly by the balance sheet of an institution, also becomes more costly to obtain. Volume of issuance in the commercial paper market falls and the spreads of commercial paper yields over Treasury bill yields rise (Gatev and Strahan, 2006). Firms find it difficult to rollover or renew lines of funding from banks. Banks also face higher costs of funding. The interbank market for liquidity does not function smoothly. Many regulators during the recent subprime crisis expressed concern that there was "gridlock" in the interbank market: banks were unwilling to lend to each other and instead hoarded their reserves (McAndrews and Potter, 2002).

Many observers refers to a *flight to liquidity* during a crisis: Investors scramble for liquidity, exiting illiquid investments and seeking liquid investments during a crisis. They buy secondary market assets that have high market liquidity, and prefer to hold portfolios in short-term safe claims such as bank deposits that are de-facto liquid. Empirical work finds that the price differences between less and more liquid Treasury bonds, which are otherwise similar, rises during crises (Krishnamurthy, 2001). Price differences between less liquid corporate bonds, mortgage-backed securities, or Agency bonds and more liquid Treasury bonds also

[19] These different senses of liquidity I have presented are alternative ways of looking at a particular equilibrium. In some cases the distinctions may seem contrived. For example, funding liquidity is a term used to describe how easy it is to raise debt financing against an asset, while market liquidity refers to how easy it is to sell the asset outright. But, debt financing is really a contingent sale of the asset; the lender owns the asset if the borrower does not repay the loan, so that the lender must think about the market liquidity of the asset in setting the terms of the loan.

rise (Longstaff, 2004, Gabaix, Krishnamurthy, and Vigneron, 2007, Krishnamurthy and Vissing-Jorgensen, 2008).

The flight to liquidity is assumed in my model in that there is an exogenous liquidity shock suffered by the hedge funds. One way of interpreting this shock is that the end-investors of the fund are scrambling for liquidity and pulling their money out of the fund. In Diamond and Dybvig's (1983) model of bank runs, some households are assumed to receive a preference shock that motivates them to pull their money from the bank. There is a deeper question of where these "liquidity" shocks arise; see the lengthy discussion in Footnote 4.

The final notion of liquidity that appears both in my model and the literature is *macroeconomic or monetary liquidity*. The central bank or Treasury has control over the supply of government-backed assets. These assets include money and bank reserves provided by the central bank as well as Treasury bonds, which are among the most liquid assets in the marketplace. During crises, the central bank "supplies" liquidity to ease the crisis, by for example, expanding the supply of bank reserves. The central bank also directly lends reserves to commercial or investment banks through the discount window, accepting less liquid assets as collateral. In the subprime crisis, the Fed has conducted swaps of (less liquid) mortgage-backed securities for (more liquid) Treasury securities through the Term Securities Lending Facility. One can also see Treasury Secretary Paulson's original proposal to buy subprime mortgages in this light. The transaction absorbs less liquid assets onto the government's balance sheet, placing more liquid Treasury securities in private hands.

In the models I have presented, the government can improve outcomes when it absorbs less liquid assets onto its balance sheet, providing more liquid government-backed assets to the private sector in return. The various policies I have discussed can all be thought of in this light. For example, injecting equity capital in the financial sector, or offering loans with lower margin requirements through the discount window are examples of policies where the government accepts a stake in the distressed asset, providing cash to the financial sector in return. These transaction enhance the financial sector's balance sheet liquidity and drives the benefit to policy.

5 Conclusion

This paper has described two amplifications mechanisms – through balance sheets and through uncertainty – that operate during liquidity crises and studied the scope for ex-ante and ex-post central bank policies under each mechanism. I have discussed the two mechanisms separately for pedagogical purposes, but there may be interesting ways in which they interact. Let me conclude by offering some thoughts on such interaction effects.

In the uncertainty model, agents are uncertain over the liquidation shock probabilities of other agents. I have shown how the balance sheet mechanism creates an endogenous source of liquidation shocks that depends on the leverage of agents. Suppose that agents are uncertain about the leverage of other agents. Then, there will be uncertainty over the strength of the balance sheet mechanism – are we in the multiple equilibrium region or not? – and this can lead to a larger liquidity discount at date s.[20]

The interaction may also run in the other direction. In the recent subprime crisis, I have argued that the initial market dynamic was driven by uncertainty. As investors grappled with the complexities of credit market instruments, their behavioral response caused asset prices to fall. At some point, balance sheet constraints became an issue and the effects highlighted by the balance-sheet/asset-price feedback began to dominate the market.

Another interaction that seems interesting to study has to do with the informativeness of market prices. Routledge and Zin (2005) develop a micro-structure model of asset trade in which Knightian uncertainty leads to a trading halt and widening of bid-ask spreads. Their model suggests that uncertainty inhibits the process of price discovery, rendering market prices uninformative about fundamental value. This too may be interestingly related to balance sheet effects. Accounting rules require that banks mark their books to market prices. However in an environment of uncertainty, where market prices are suspect, such mark-to-market accounting becomes difficult (see Easley and O'Hara, 2009), and can possibly trigger balance sheet amplifiers.

These observations can also shed light on how a market recovers from an uncertainty-driven crisis. It is clear from the model I have outlined as well as the historical examples I have given that the uncertainty crisis is only resolved over time as investors understand where they went wrong and formulate new models of the world; in short, as the uncertainty is resolved. Part of this process involves information revelation. What mistakes have investors made? Which investors have large exposures to the relevant assets, and how big are their losses? In an environment where the price discovery mechanism is impaired, information revealed from accounting statements is hard to interpret. Further, in an environment where balance sheets are weak, a

[20] As another example, consider that in 1998, the Russian default triggered a liquidation event in hedge-fund dominated markets. The resulting unexpected correlation among market prices was a surprise to most market participants and triggered an uncertainty dynamic.

financial institution may be reluctant to realize losses, impeding information revelation. These forces tend to perpetuate an uncertain environment, which may be one factor behind the duration of the subprime crisis. Indeed, from this perspective, a benefit of the stress-tests performed by the Treasury in the current crisis is that they force information revelation and reduce uncertainty.

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